The "Snow Plow Theory"* of Early-Arriving Tsunamis

* completely contrived term by this author, not a scientific term or theory

What is a Tsunami?

"Tsunami" became a more common household word after the devastating M9.1 Sumatra earthquake on December 26, 2004. The world now has a greater awareness of what a tsunami is and what it can do.

The tsunami created by the 2004 M9.1 Sumatra earthquake. (Courtesy of EarthScope)

A tsunami is generated when there is sudden up or down movement of the seafloor, typically from slip on a fault or a landslide. A landslide will create a depression on the ocean's surface above. Slip on a fault can create a depression if the ocean floor drops, or a "hill of water" on the ocean's surface if the ocean floor has uplift. The sea surface above the shifted seafloor is suddenly either higher or lower than the otherwise flat ocean, and in either case, the water will move in order to make the ocean surface flat again. The movement of the water creates a wave that moves outward in all directions, much like when a rock is thrown into a pond. As the volume of water moves across the ocean, it may die out before it reaches a land mass. Or it can rise up as a large swell as it approaches land due to shallower water near the coast. Certain coastal geometries, like harbors, for example, can make the swell even larger as it is squeezed into a smaller horizontal space.

What causes displacement of the seafloor during an earthquake? We know that both large-scale and small-scale sudden uplift of the crust can occur in large earthquakes along subduction zone boundaries where an oceanic tectonic plate is subducting, or diving, under a continental plate. But if we want to understand the hazards in a particular location, and have a better idea of what to expect when there is a large earthquake in these places, we need to learn more.

Scientific Staff

- Peter Haeussler

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The M9.2 Alaska Earthquake and Tsunami

The M9.2 1964 Good Friday, Alaska earthquake ruptured a massive 800km long by 250km wide fault, with two areas that released the most energy – near Kodiak Island and beneath Prince William Sound. In many places the tsunami came ashore more quickly than expected from uplift along the deep subduction zone interface. For example, a large tsunami locally impacted the coastal town of Seward only 1.5-2 minutes after the start of shaking, and then 30 minutes after the earthquake another large tsunami inundated Seward and many other towns along the coast of Prince William Sound. Yet another tsunami later moved out across the ocean to affect distant coastlines as well. Sudden displacement of the seafloor must have occurred somewhere close to shore, but where and why?

The Seward Highway at the head of Turnagain Arm near Anchorage after the quake.

Montague Island is the southernmost island in Prince William Sound, and it lies 140km inland from the subduction zone boundary – a perfect place to look for clues to what happened. Shortly after the earthquake, scientists discovered 9m of unexpected uplift along the Montague Island shoreline caused by slip on the Patton Bay Fault. This location was farther from the coast than the landslide, but closer than the subduction zone boundary far offshore near the oceanic trench. They concluded that the Patton Bay fault was the source of the uplift that produced the tsunami that reached the shore so quickly. Subsequent investigations identified local underwater landslides as the source of the first tsunami that arrived at Seward within just a few minutes after the earthquakes started. Later research clarified that the Patton Bay Fault was the first documented example of a "megathrust splay fault", or a fault that connects to the subduction boundary but provides a shortcut for sudden plate motion to reach the surface. Why was the fault motion and uplift occurring on these splay faults rather than the subduction boundary?

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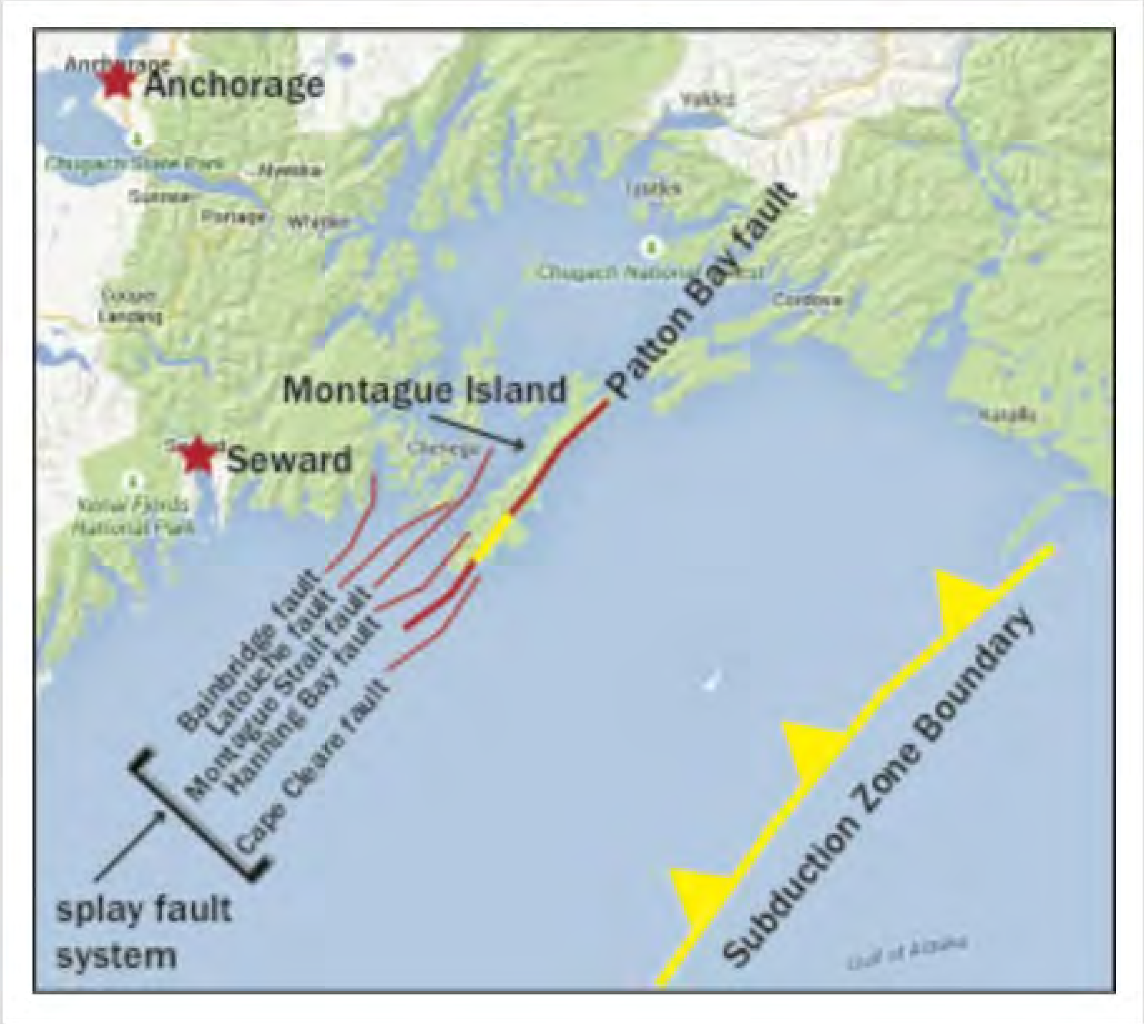
Splay Faults

Not only was the Patton Bay splay fault system far away from the main subduction zone boundary, but also the tsunami it caused arrived quickly and caused extensive, if localized, damage. Scientists wondered if this splay fault scenario was common in other subduction zone areas, and if so, how could it be identified? If they could learn more about what happened during the 1964 event, then they may be able to spot other areas that could give rise to tsunamis that were generated closer to the shoreline than the main subduction boundary, and residents could be warned immediately to evacuate if there were a large earthquake.



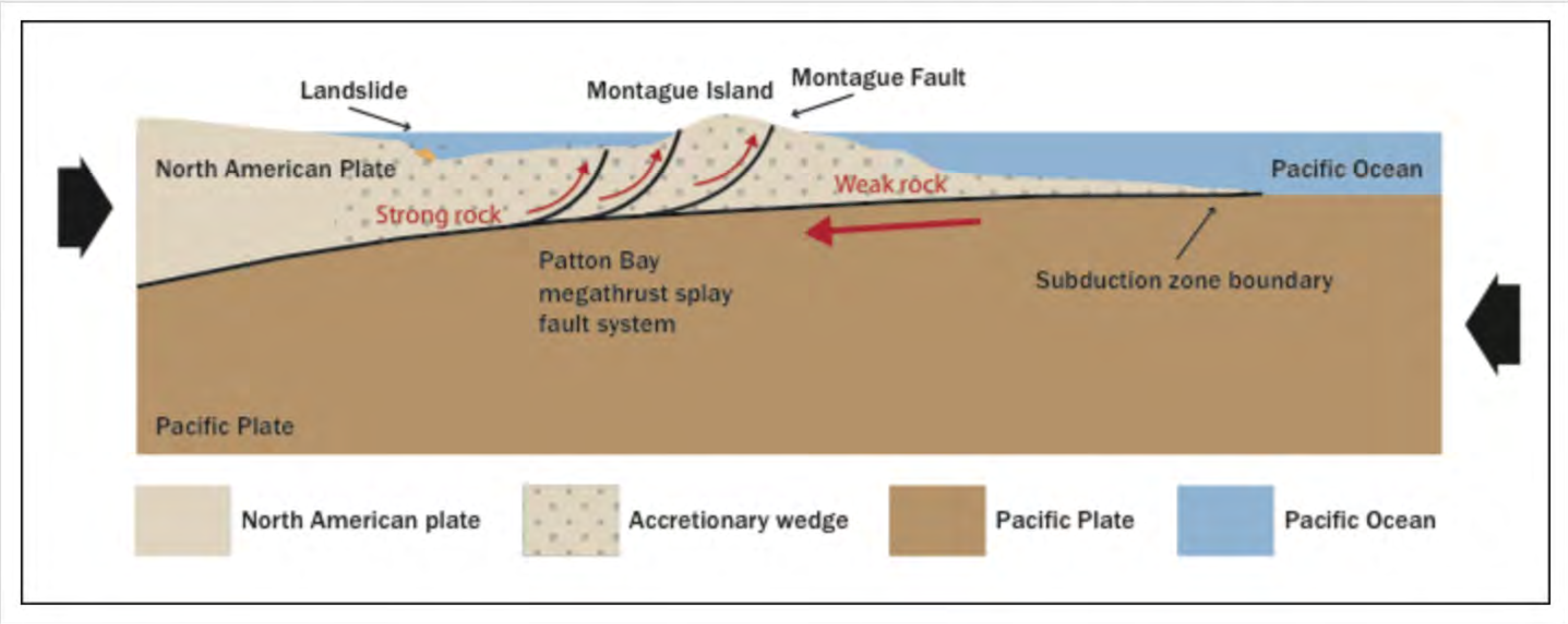
Location map of the Prince William Sound showing the subduction zone and the splay fault system nearer the shore. The yellow lines show the subduction zone and the extent of one fault that was known before this study. The red lines show the splay faults that were mapped during this investigation.

With more work, scientists found that megathrust splay faults appear to be common to many subduction zones. Splay faults don't always rupture during a large subduction zone earthquake, so scientists wondered why did they rupture in some places sometimes, in other places often, and in yet other locations, rarely. These thrust faults seemed to extend from the sea floor all the way down to the subduction zone boundary. The "thrust" means that some part of the earth's crust is thrust upward. Splay faults were thought to be the cause for localized large tsunamis in subduction zone earthquakes, such as the 1932 Mexico, 1944 Japan, 1945 Persian Gulf, and the 2010 Ecuador events. However, there was no direct evidence, and the mechanism was not well known. Because splay faults are typically offshore, they are not easily accessible.

New Images of Splay Faults

New techniques to image the subsurface have recently been developed, and scientists recognized that they could be used to study the megathrust splay faults in Prince William Sound. The results showed that there are many active and inactive splay faults along parts of the Aleutian subduction zone, extending far beyond Montague Island. The imaging also showed more detail about the splay faults than scientists were able to see previously, and so they were able to figure out how they work and how they cause tsunamis, at least in the Prince William Sound.

They found uplifted blocks consist of accretionary wedge material that is squeezed up by contraction in this area when there is slip on the main subduction zone boundary. An accretionary wedge is a collection of material that is scraped off the top of the oceanic plate as it dives under the continental plate. The wedge grows each time there is slip on the subduction boundary. The oldest material in the wedge nearer the shore becomes strong and more rock-like from compression, while the younger, newest, material further from shore is still weak.



Cartoon cross-section of the subduction zone boundary showing the splay faults.

It works similar to the way the snow piles up on your snow plow or snow shovel as you push it across the driveway after a snowfall. First the snow accumulates on the shovel, and then as you continue to push it starts piling up in front of the shovel and compacting the snow that's already on the shovel. Splay faults within the wedge of snow allow the pile to shorten and thicken, then turn off when the pile is too thick and compacted. (See The Thrust Belt in My Driveway, blog page by a geology professor, for some excellent photos.) Similar to the way snow wedges form on a snow plow or snow shovel, the detailed subsurface images collected in Alaska showed that the splay faults are concentrated at the boundary between the stronger compacted rocks nearer the land and the weaker rocks nearer the ocean in the accretionary wedge.

Repeated Movement on Splay Faults

The images also captured several million years of tectonic history. Every time there was a large subduction zone earthquake in the Prince William Sound area, it has been accompanied by vertical movement on the Patton Bay splay faults and their offshore equivalents. So the 1964 event was not just a fluke. What does this mean? It means that every time there is a large subduction zone earthquake in the 1964 location, there will likely be vertical uplift on the splay faults that will cause a tsunami that may arrive faster, and be higher, than what would be predicted from slip on the underlying megathrust alone.

Splay faults above subduction megathrusts are present around the world. Scientists know this same situation must be present in other subduction zone areas; they just don't know where all those areas are yet. But now they know what to look for. The tsunamis caused by the splay faults can reach the shoreline quickly, reach great heights, and travel inland farther than other types of tsunamis. The identification of megathrust splay faults near populated shorelines and the education of nearby residents could help those communities be prepared for a future potential tsunami.

-written by Lisa Wald, U.S. Geological Survey